

and Yager, 2000). See Lipman (1976) for detailed description of the Silverton Volcanics. Sapinero Mesa Tuff (Oligocene)—Nonwelded gray to densely welded red-brown rhyolitic ashflow tuff. Contains 2–5 percent phenocrysts of plagioclase, with lesser amounts of sanidine, biotite, and trace augite. Outflow derived from the San Juan and Uncompangre calderas. Mean  $^{40}$ Ar/ $^{39}$ Ar age determined from sanidine is 28.19±0.03 Ma (Bove and others, 2001).

Eureka Member and Picayune Megabreccia Member of Sapinero Mesa Tuff (Oligocene)—Eureka Member is partly welded light-gray to densely welded red-brown rhyolitic to dacitic(?) ash-flow tuff containing 5 percent phenocrysts of plagioclase, sanidine, and biotite. Unit is the intracaldera member of the Sapinero Mesa Tuff. Picayune Megabreccia Member consists predominantly of older andesitic to dacitic blocks (often enclosed in a Eureka Member tuff matrix) that caved into the San Juan caldera during caldera collpase. Exposures of the Picayune Megabreccia Member crop out about 2.5 km north of Eureka town site. Remanent magnetic polarity: reverse. Maximum exposed thickness (base not seen) is 800 m

Dillon Mesa Tuff (Oligocene)—Nonwelded gray to densely welded red-brown rhyolitic ash-flow tuff. Mineralogy is similar to that of the Sapinero Mesa Tuff (Ts). The Dillon Mesa Tuff is generally thinner and less densely welded than the Sapinero Mesa Tuff. Mean <sup>40</sup>Ar/<sup>39</sup>Ar age determined from sanidine is 28.40±0.04 Ma (Bove and others, 2001). Probably derived from the Uncompangre caldera. Remanent magnetic polarity: reverse. Thickness 0–100 m Blue Mesa Tuff (Oligocene)—Nonwelded gray to densely welded red-brown ash-flow tuff. Contains about 5 percent phenocrysts of plagioclase, sanidine, and biotite. Probably derived from the Lost Lake caldera (Lipman, 1976). Mean <sup>40</sup>Ar/<sup>39</sup>Ar age determined from sanidine is 28.4±0.07 Ma (Bove and others, 2001). Remanent magnetic polarity: reverse. Thickness

0–250 m

Ute Ridge Tuff (Oligocene)—Nonwelded gray to densely welded gray-brown to red-brown dacitic ash-flow tuff. Unit consists of 50 percent phenocrysts of plagioclase, sanidine, biotite, and augite. Derived from the Ute Creek caldera. Mean 40Ar/39Ar age determined from sanidine is 28.63±0.05 Ma (Bove and others, 2001). Remanent magnetic polarity: reverse. Thick-

San Juan Formation (lower Oligocene)—Intermediate-composition lava flows and volcaniclastic deposits consisting mostly of mudflow breccias containing dark intermediate-composition volcanic clasts with some conglomerate and sandstone; flows commonly contain hornblende. Volcaniclastic deposits preserved as clastic aprons on the slopes of and between penecontemporaneous stratovolcanoes. Thickness 0–600 m Tuff of Imogene Pass Member of San Juan Formation (lower Oligocene)—Dark-brown, ande-

sitic to dacitic ash-flow tuff. Corresponds to unit Tse of Burbank and Luedke (1964). Ash flows formed as a result of stratovolcano collapse near Red Mountain and Imogene Passes. Ash flows are best preserved in the Imogene Pass area but grade laterally into basal lag breccias with blocks as large as 5 m that are enclosed in a pyroclastic matrix. Thickness 0–80 m **Telluride Conglomerate (Eocene)**—Gray to brownish-red conglomerate and sandstone. Consists of Precambrian, Paleozoic, and Mesozoic, cobble- to boulder-size clasts in an arkosic, silty to

#### PRE-TERTIARY ROCKS

sandy matrix. Thickness 0–60 m

base. Thickness about 100 m

stone, and conglomerate. Thickness 0-25 m

careous shale and sandstone. Thickness 0–15 m

Granodiorite (Late Cretaceous)—Light-gray, porphyritic granodiorite laccolith restricted to northwest corner of map area Mancos Shale (Upper Cretaceous)—Mostly dark gray marine shale. Thickness about 200 m; however, unit much thicker to the south Dakota Sandstone (Upper Cretaceous)—Light-gray to brown sandstone with interbedded siltstone and carbonaceous shale; commonly contains chert-pebble conglomeratic sandstone at

Morrison Formation (Upper Jurassic)—Basal part of unit consists of yellowish-white to buff, crossbedded, fine- to medium-grained sandstone with lenses of gray to green variegated mudstone. Upper part of unit consists primarily of variegated calcareous mudstone. Thickness Wanakah Formation (Middle Jurassic)—Green to red-brown calcareous mudstone and siltstone with thin limestone and sandstone interbeds near top of unit. Thickness 0-30 m ntrada Sandstone (Middle Jurassic)—Light-tan, fine-grained, crossbedded sandstone. Thick-

Dolores Formation (Upper Triassic)—Brownish-red siltstone and sandstone with interbeds of limestone and quartz-pebble conglomerate. Thickness about 40 m Cutler Formation (Lower Permian)—Reddish-brown micaceous shale, arkosic sandstone, and conglomerate; locally calcareous. Thickness 0–150 m Hermosa Formation (Upper and Middle Pennsylvanian)—Red-brown arkosic sandstone, and interbedded fossiliferous greenish-gray shale, sandstone, conglomerate, and marine limestone. Thickness 0–550 m Hermosa and Molas Formations, undifferentiated (Pennsylvanian)—Reddish-brown shale, sandstone, and conglomerate

Molas Formation (Middle and Lower Pennsylvanian)—Reddish-brown calcareous shale, sand-

Ignacio Quartzite (Upper Cambrian)—Light-gray quartzite, sandstone, and siltstone; locally con-

**\_eadville Limestone (Lower Mississippian)**—Gray, dense limestone with a few basal sandy layers; chert and red shale interbeds near top. Thickness 0-60 m eadville and Ouray Limestones, undifferentiated (Lower Mississippian and Upper Devonian)—Altered, mineralized, and recrystallized limestone near Ironton Park and in Silverton and Howardsville 7 1/2' quadrangles. Thickness 0-65 m Ouray Limestone (Upper Devonian)—Light-gray dolomite and limestone. Thickness 0–15 m Elbert Formation (Upper Devonian)—Tan, thin-bedded dolomitic limestone and interbedded cal

glomeratic in lower part; maximum thickness 17 m Indifferentiated rocks (Precambrian)—Gray and black to brown argillite, slate, quartzite with slate partings, schist with quartz partings, and gneiss

Fault—Dashed where concealed or inferred; bar and ball on apparent downthrown block Mineralized, altered veins and fissures—Location dashed where inferred beneath Quaternary ———— San Juan caldera, topographic southern margin—Dashed where approximately located

Strike and dip of bedding Strike and dip of foliation

#### INTRODUCTION

Economic and, later, geologic interest focused on the upper Animas River watershed in the vicinity of Silverton, Colo., initially because of the discovery of gold in the region in 1870 (Sloan and Skowronski, 1975). Regional and topical geologic investigations in the area have spanned the era from the late 19th century to the present (Ransome, 1901; Cross and others, 1905; Varnes, 1963; Burbank and Luedke, 1964; Steven and others, 1974; Luedke and Burbank, 1975a, b; Lipman, 1976; Luedke, 1996). Many of these geologic investigations were concerned with (1) the extensive base- and precious-metal mineral deposits dispersed throughout he region and (2) a remarkable and varied stratigraphic and structural geologic history. The Tertiary volcanotectonic history and related events of mineralization are responsible not only for the mineral deposits but also for alteration of the Tertiary volcanic rocks in or near the San Juan and Silverton calderas (Casadevall and Ohmoto, 1977; Bove and others, 2000, 2001; Yager and others, 2000). Weathering of the altered near-surface volcanic rocks produces acidic waters that transport major and trace elements into surface waters. The purpose of this geologic compilation is to provide the U.S. Geological Survey, Animas River watershed, Abandoned Mine Lands (AML) project a geologic map at a suitable scale for geospatial analysis. This map will be used to interpret geochemical, geophysical, hydrologic, and biologic data sets within a geologic framework. Diverse data acquired during the Animas River watershed AML project will also be used by Federal land-management agencies in developing effective mined-land remediation strategies (Buxton and others,

# GEOLOGIC SETTING OF THE ANIMAS RIVER WATERSHED STUDY AREA

# PHYSIOGRAPHIC SETTING

The map area is located in the rugged and spectacular San Juan Mountains in the western San Juan volcanic field, southwestern Colorado (fig. 1). Topographic relief in the project area exceeds 1,000 m, with elevations reaching more than 4,000 m above sea level. The ecoregion is classified as the southern Rocky Mountain Steppe (Bailey, 1995). The watershed receives as much as 88–100 cm of precipitation principally as snow in the winter and early spring months (Daly and others, 1994); brief, but intense, summer thunderstorm activity produces stormwater runoff throughout the summer months. U.S. Highway 550 provides access to the map area from either Montrose or Durango, Colo. Major streams that are part of the upper Animas River area include Cement and Mineral Creeks, located north and west, respectively, from the town of Silverton, and the Animas River in the east and northeast (fig. 1).

# GEOLOGIC SETTING

The general stratigraphy of the map area consists of a Precambrian crystalline basement overlain by Paleozoic and Mesozoic sedimentary rocks and by a Tertiary volcanic cover (Luedke and Burbank, 1963; Steven and others, 1974; Lipman, 1976). Tertiary volcanism in the San Juan volcanic field began between 35 and 30 Ma with the eruption of intermediate-composition lava flows, pyroclastic flows, and mudflows. The oldest Tertiary volcanic rocks, the San Juan Formation, consist of mudflows, pyroclastic flows, and lava flows. Caldera-related eruptions commenced in the western San Juan Mountains with formation of the (28.2 Ma) San Juan caldera and the nearly coincident Uncompander caldera, followed by the nested (27.6 Ma) Silverton caldera (Lipman and others, 1973; Bove and others, 1999). Caldera-bounding arcuate ring fractures and tangential radial fractures preserved near the periphery of the

calderas provided pathways for intrusive magmas and later hydrothermal fluids (fig. 1). These Tertiary volcanotectonic structures occur as regionally pervasive features that extend for thousands of meters. Secondary caldera-related structures such as apical grabens were also later extensively mineralized and developed as post-caldera collapse magma intruded and domed the central cores of these 15-km-wide calderas (Casadevall and Ohmoto, 1977). Caldera-related structures also provided pathways for eruption of lavas that infilled the calderas. For example, San Juan caldera collapse was followed by ring fracture eruption of post-collapse, intermediatecomposition Silverton Volcanics lava flows that infilled the caldera (Lipman and others, 1973). Multiple, intermediate- to silicic-composition, post-caldera-collapse porphyries intrude the San Juan Formation and Silverton Volcanics along the margin of the Silverton caldera (fig. 1). These intrusions usually postdate caldera formation by at least 1 m.y. (Ringrose, 1982). Regional tilting and uplift in the San Juan Mountains during latest Miocene to Pliocene time resulted in significant erosion and downcutting to expose a hydrothermally altered and intensely mineralized terrain (Steven and others, 1995). Extensive Pleistocene glaciation and accompanying erosion throughout the region further exposed the mineralized terrain to weathering processes. Weathering of minerals in hydrothermally altered rocks and in surficial deposits (Bove and others, 2000; Yager and others, 2000) results in acidic and metal-rich streams throughout the Animas River watershed study area.

### MAP COMPILATION APPROACH

Most map data were transferred to stable base materials and scanned or digitized. Digital map data were converted into ARC/INFO and projected to the Universal Transverse Mercator (UTM) geographic projection (zone 13). This is the projection used for other cartographic base information available for the Animas River watershed, AML project. The compilation scale was 1:24,000; sufficient data were generally available from existing geologic maps to maintain continuity in map units and structural features across map boundaries. Parts of the Howardsville and the Silverton 7 1/2' quadrangles were not mapped in as much detail as the remainder of the map area. Thus, certain units and structural features and veins are not displayed in as much detail as is evident in other areas.

Units within the Silverton Volcanics, such as the Burns and Henson Members and the pyroxene andesite member (Lipman, 1976), were not mapped separately for this compilation due to the lack of corresponding data for parts of the Howardsville and Silverton 7 1/2' quadrangles. Quaternary units were generalized for the purposes of this compilation. Detailed 1:24,000-scale surficial geology is available for the Animas River from Durango to Silverton and for its major tributaries in the Animas River watershed study area (Blair and others, 2002). Not all veins were compiled from existing maps. Vein orientation and vein density are generalized

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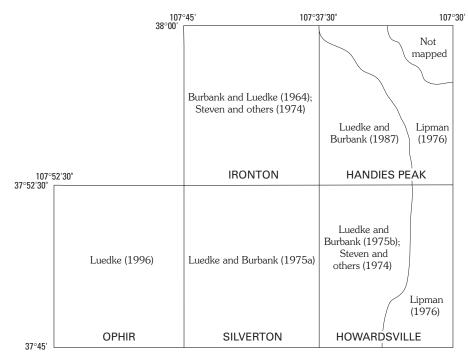
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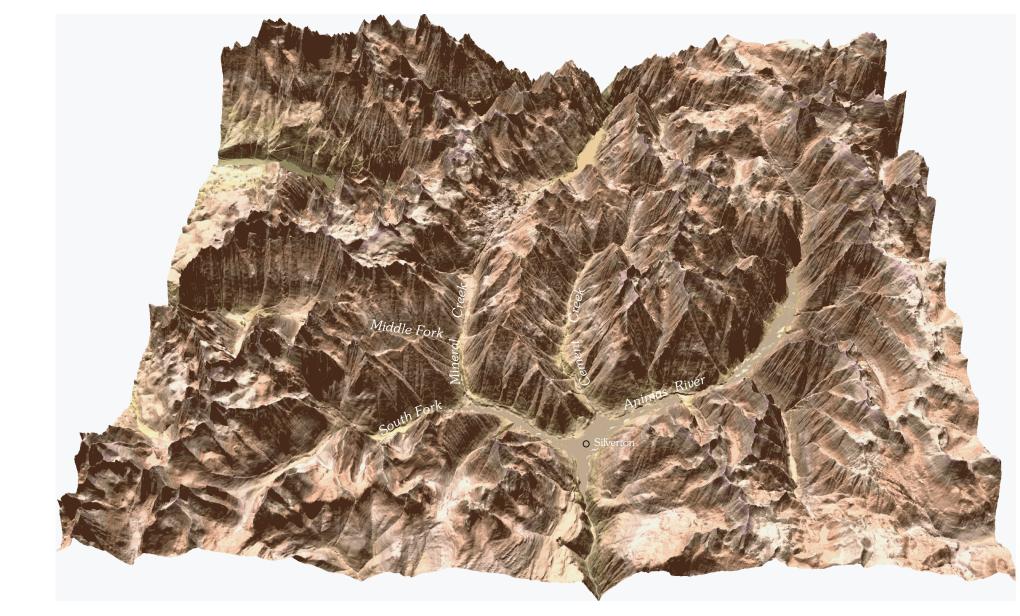
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### **ACKNOWLEDGMENTS**

The authors wish to thank Thomas J. Casadevall (USGS) and Karen Budding (formerly USGS) for their contributions regarding the geochronology and paleomagnetic characteristics of the units mapped previously as the Gilpin Peak Tuff (Burbank and Luedke, 1964). Their work along with newly acquired isotopic dates on these units (Bove and others, 2001) permitted determination of the ages and caldera-related sources of these units. Reviews by Karl V. Evans, Peter W. Lipman, and Alessandro J. Donatich (USGS) are appreciated. We have benefitted from discussions with Robert G. Luedke (USGS) and are greatly appreciative of his early review



INDEX MAP SHOWING 7 1/2' TOPOGRAPHIC QUADRANGLES AND AREAS OF MAPPING RESPONSIBILITY USED FOR THIS GEOLOGIC COMPILATION



ARC/INFO hillshaded perspective relief model indicates the rugged relief of the upper Animas River watershed, Abandoned Mine Lands study area. View is to the north from an altitude of 30,000 ft, with a sun azimuth of 50°; no vertical exaggeration was used. Cropping of the image at its edges combined with the viewing perspective parameters used results in a slightly exaggerated appearance of the topography. Data sources include 10 m digital elevation models available from the U.S. Geologi-